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Effect of elastic modulus variation during plastic deformation on uniaxial and multiaxial ratchetting simulations

Mohammad Abdel-Karim

Industrial Engineering Department, Faculty of Engineering, Fayoum University, Fayoum 63111, Egypt

A R T I C L E I N F O

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A B S T R A C T

In order to identify different variables that affect ratchetting simulations, variation of elastic modulus during loading and unloading is considered and discussed based on the experimental observations which pointed out by Morestin and Boivin (1996), Ishikawa (1997), Cleveland and Ghosh (2002), Zhou et al. (2005) and recently by Khan et al. (2009a,b,c). Then the effect of such variation on simulations is scrutinized from the theoretical point of view by considering simulations of ratchetting experiments conducted on stainless steel 304L by Hassan et al. (2008) using the well-known Armstrong–Frederick model. It is shown that, using two different values for the elastic modulus during loading and unloading could have a significant effect on simulations of uniaxial ratchetting. On the other hand, such significant effect hardly occurs in the case of simulations of biaxial ratchetting experiments under consideration. The importance of such findings is that the excessive ratchetting over-prediction resulting from any specific kinematic hardening rule is expected to decrease significantly by taking into consideration this effect. In this case, modeling of kinematic hardening rules could necessitate more attention and reconsideration.

1. Introduction

Throughout the last three decades, numerous studies have attempted to determine the controlling and fundamental factors that affecting ratchetting and to find appropriate ways to replicate these factors into the scheme of constitutive modeling to be able to simulate experimental responses as accurate as possible. To obtain a better appreciation for this phenomenon, i.e., ratchetting, it is worth to note that ratchetting is concerned with secondary deformation accumulating cycle by cycle in the direction of mean stress, therefore, it is not easy to describe it quantitatively.

During simulations of this critical phenomenon (i.e., ratchetting), similar to simulations of other material responses, elastic behaviour is usually assumed to be constant. It is worth to remember that elastic behaviour is the result of atomic bond stretching and it is assumed to be linear because this is a good first order approximation. However, exact application of elastic theory includes higher order terms that lead to a small amount of nonlinear recovery (Wong and Johnson, 1988). In addition, different experiments have indicated that during plastic deformation, the elastic modulus (E) might change significantly (Cleveland and Ghosh, 2002; Luo and Ghosh, 2003; Khan et al., 2009a,b,c). In this case, it is expected that such variation could have a significant influence on small-scale plasticity as in ratchetting. Moreover, early yielding under reversed loading, known as Bauschinger effect, is yet another reflection of this small-scale plasticity. The Bauschinger effect has been explained in terms of the easy motion of piled up dislocations and separating of dislocation structures when the loading direction is reversed (Stout and Rollett, 1990). In the mechanics literature, the phenomenology of the Bauschinger effect is empirically described as kinematic hardening (translation of yield surface). Attempts have been made to describe a portion of the nonlinear recovery behaviour in kinematic hardening models (see the review paper of Chaboche, 2008). However, such mathematically artificial models are not physically based, and fail to predict realistic quantitative results under some conditions (Abdel-Karim, 2009).

Throughout the context of studying different variables that might affect ratchetting, influence of variation of elastic modulus during loading, unloading and re-loading has not been considered yet, neither experimentally or theoretically. In simulations and within the scheme of constitutive models that replicate ratchetting responses, it is common during plastic deformation assuming constant and identical values for the elastic modulus throughout loading, unloading and re-loading. However, as aforementioned, different experiments indicated that during plastic deformation, the value of the elastic modulus might change significantly. In this case, such change could have a considerable effect on simulation of ratchetting especially

E-mail addresses: karim12004@yahoo.com, mak02@fayoum.edu.eg.

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uniaxial ratchetting, since it deals with small accumulation of plastic strain cycle by cycle. This point has not been studied yet. Therefore, it is highly recommended to examine and scrutinize the influence of variation of the elastic modulus during plastic deformation on overall ratchetting simulations, which is the aim of this work.

2. Background

The necessary basic fundamental concepts to describe material behaviour under general stress states can be defined mainly according to the following three concepts:

(i) Initial yield criterion: specifies the state of stress for which plastic flow will start.
(ii) Associated flow rule: relates plastic (inelastic) strain increment with the stress and its increment.
(iii) Hardening rule: describes the changes in the yield surface as work hardening proceeds.

In simulating ratchetting, it is common to consider hardening rules which describe initial and subsequent yield surface, however to have a general and more accurate simulations for material behaviours, the other two factors (i.e., yield criterion and flow rule) should be considered as well. Particularly, most researchers agree with the applicability and correctness of associated flow rule, which states that the plastic strain increment will be in the direction of the outward normal to the yield surface. However, up to now, there are many and different suggestions about hardening rules, which are out of our topic.

Regarding the initial yield surfaces, we will emphasis merely in this work on some available experimental investigations and observations. In fact, the method used to determine the yield point affects the experimental application of methods for estimating elastic modulus and the elastic range. Fundamentally, the determination of the yield surface depends on two different concepts (Michno and Findley, 1976):

1. The choice of a suitable test specimen
2. Definition of yield

In literature, the thin-walled tubular specimen has been found to be very suitable as reported by Drucker (1956, 1667), however other different types and specimen methods used can be found in details elsewhere (Michno and Findley, 1976; Wu and Yeh, 1991).

The definition of the yield is very important since different yield surfaces result from different definitions (an exception is mild steel which exhibits a well-defined lower yield point elongation). In addition, such different definitions could significantly affect simulations especially, if yield surface distortion is considered. For work-hardening material, the definition of yield to accept is not straightforward as clearly shown in Fig. 1, which illustrates some possible definitions that have been used and/or are currently in use. The terms shown in this figure can be stated as follows (Michno and Findley, 1976):

(A) The proportional limit;
(B) A small measurable permanent set (in the range of 10 microstrain to 50 microstrain);
(C) The conventional engineering offset of 0.2% strain;
(D) Point of tangency of stress–strain curve with a multiple of elastic slope;
(E) and (F) Extrapolation method in which (E) neglects the elastic deformation whereas (F) includes it (Taylor-Quinney definitions).

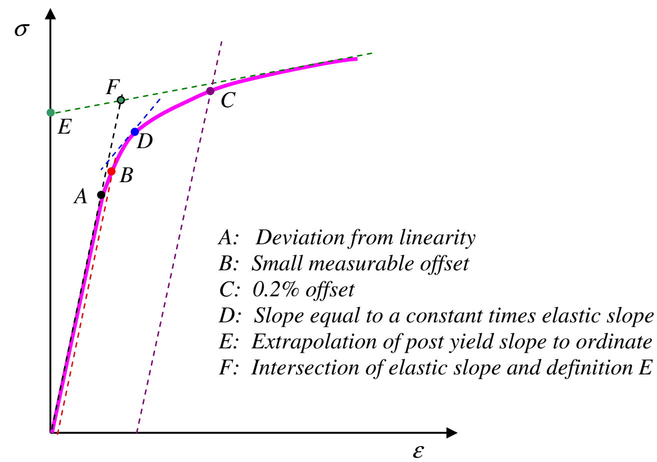

Fig. 1. Various definitions of yield (Michno and Findley, 1976).

The applicability for any of these methods depends on many factors. For example, technically it is difficult to have two identical specimens. In addition, economically it is desirable to determine a whole series of initial and subsequent yield surfaces by use of only one specimen. This leads to the proportional limit definition of yield.

Incidentally, applications of small offset definition or the proportional limit definition of yield (or departure from linearity) to materials with intrinsic knees in their stress–strain curves allow many yield probes to be made on a single specimen (see for example: Naghdi et al., 1958; Ivey, 1961; Bertsch and Findley, 1962; Williams and Svensson, 1970; Phillips and Tang 1972; Shiratori et al., 1976; Stout and Martin, 1985; Ishikawa 1997; Wu and Yeh 1991; Kowalewski and Sliwowski, 1997). A proof strain of 5 or 10 micron may also be classified as a proportional limit method (Helling et al., 1986). This method allows barely enough plastic strain to define clearly the start of the yield point. In this manner, one specimen can be used to determine the whole initial yield surface and the subsequent yield surfaces. It should be noted that the yield surface based on this definition exhibits strong translation, distortion and Bauschinger effect, but little cross effect.

The definition of yield is particularly difficult for materials which do not exhibit a sharp knee at yield. The proof strain method defines the yield point as the point for which a predetermined amount of plastic strain is developed. Usually, a value of 0.2% offset strain is assumed in engineering applications. This conventional 0.2% offset definition of yield is too large if more than one probe is to be made per specimen. In actual research, the value of offset strain can be different. For example, Mair and Pugh (1964) used 10^{-3} as proof strain, Shiratori et al. (1976) used 2×10^{-4}, Bertsch and Findley (1962), Michno and Findley (1974), Ellis et al. (1983) and Khan et al. 2009a,b,c used 10 microstrain, Ishikawa (1997) used a 50 microstrains, Wu and Yeh (1991) used 5 microstrains and Trampczynski (1992) used 500 microstrains offset strain in the determination of yield. Moreover, Szczepinski and Miastkoshi (1968), Ohash et al. (1975) and Niitsu and Ikegami (1984) used various proof strains to determine a field of equivalent plastic strain surfaces. This method leads to expansion, displacement, as well as distortion of yield surface. Again, in order to determine a yield surface, the method requires a large number of identical specimens.

Incidentally, the definition of yield by means of a 5 microns equivalent plastic strain has gained popularity in the literature (Helling et al., 1986; Helling and Miller, 1987 and Wu and Yeh, 1991). One of the reasons for the popularity is that the definition of yield of 5 microns is close to that based on the proportional limit